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Numerical Simulation and Validation Study of Wetdeck Slamming on High Speed Catamaran

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ABSTRACT

This paper presents a numerical simulation method for predicting the wetdeck slamming of a high-speed catamaran. The numerical simulation method is built upon the framework of the Large Amplitude Motion Program (LAMP). LAMP is a time-domain potential flow panel code that solves the 3-D wave-body hydrodynamics and rigid-body dynamics problems with consideration of external forces. An extension of the wetdeck slamming hydrodynamic approach of Ge, Faltinsen, and Moan (2005) has been integrated into LAMP to predict wetdeck slamming within the time domain simulation. A validation study of the numerical simulation method was carried out, which compared predicted motions and wetdeck slamming pressures to measurements from recent model tests and full scale sea trials for the U.S. Navy catamaran *Sea Fighter*, FSF-1. Comparisons were made in the time-domain with wave-by-wave response for individual runs. This paper discusses the overall numerical simulation method, the mathematical formulation of the wetdeck slamming approach, details of the *Sea Fighter* model test, full-scale trials results of the validation study, and several outstanding issues related to the numerical simulations method.

INTRODUCTION

As a high-speed catamaran advances through a seaway, it may encounter wetdeck slamming – impacts of waves on the connecting structure between the two demi-hulls. If the impact velocity is high enough, the slamming-induced impact force can cause significant local structure damage, induce global whipping response, increase transient girder loads in both longitudinal and transverse directions, and force the ship's commander to reduce speed or even abort a

mission. Because of the significant importance of wetdeck slamming to ship structural integrity and safe operation, an accurate performance analysis tool is needed to predict wetdeck slamming loads and their effect on ship motion and sectional loads.

In order to predict such effects, a numerical approach for the wetdeck slamming problem has been integrated into the framework of the Large Amplitude Motion Program (LAMP) for time domain simulation of a ship in waves. LAMP uses a 3-D potential flow panel method to solve the body-linear or body-nonlinear wave-body hydrodynamic problem and has been extensively used for the performance assessment of ship motions and wave loads over the past 18 years (Shin *et al.*, 2003). The wetdeck slamming approach is based on Ge, Faltinsen, and Moan (2005) and applies a 2-D potential flow theory for flat plate impact along a series of longitudinal strips on the wetdeck. As part of the implementation in LAMP, the original approach employed by Ge, Faltinsen, and Moan (2005) was extended for wetdeck slamming in both head and oblique seas. This approach is thereafter referred to in this paper as the GFM approach.

In the LAMP implementation, the wetdeck is subdivided into a number of longitudinal strips. Along each strip, the instantaneous wetted length and its time derivative are calculated; the relative velocity between the wetdeck and the incident wave are determined; and the impact forces are calculated by using the GFM approach. Depending on the wetdeck geometry and incident wave heading direction, the impact forces may be calculated on multiple longitudinal strips with each one having different impact velocity, location, and wetted length. Once the impact force and moment are obtained, they are added to the total force and moment and used in ship motion calculations.

In order to provide data for validating numerical methods like the present one, a series of

wetdeck slamming tests using the 1/15 scale model of the *Sea Fighter* (model 5612) was carried out at NSWCCD. In these tests, pressure panels were installed to record wetdeck impact pressure. In addition, a full scale sea trial of *Sea Fighter* was conducted in April 2006 (Fu *et al.*, 2007) to collect wetdeck slamming data in real world operating conditions. A particular challenge of using the sea-trial data for validation is to quantify the incident wave field so it can be reproduced in the numerical model. A wave field reconstruction process was employed to create a phase-resolved representation of the incident wave from the ultra-sonic sensors' measurements of the incident wave in front of the ship.

NUMERICAL SIMULATION METHOD

Framework for Ship Dynamic Simulation

In the current study, LAMP is used as the framework for the numerical simulation of hydrodynamics, wetdeck slamming, and dynamics for the *Sea Fighter* in waves. As shown in Figure 1, a key element of the LAMP simulation is the implementation of a variety of force calculation modules that represent various effects in a ship motion simulation. For the present calculations, the most relevant force modules are the 3-D hydrostatic and hydrodynamic forces, Froude-Krylov wave forces, damping forces, and wetdeck slamming forces. Once the forces are computed, a 4th order Runge-Kutta algorithm is used to integrate the six degree-of-freedom equations of motion in time.

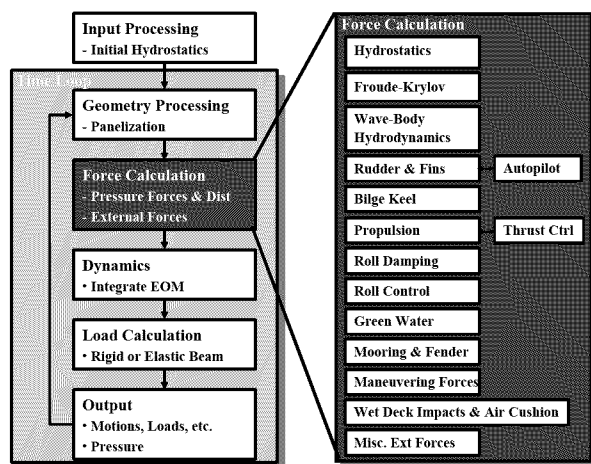


Figure 1: Framework for ship dynamic simulation

In addition to its effect on ship motions, wetdeck slamming is also likely to cause structural vibration. In order to consider this structural vibration, an integrated hydrodynamic and structure approach is required. While such an approach is currently being developed for the LAMP System, only rigid body dynamics are

considered in the LAMP results presented here.

Wave-Body Hydrodynamics

The core of the LAMP System is the 3-D solution of the wave-body interaction problem in the time-domain (Lin and Yue, 1990, 1993). A 3-D perturbation velocity potential is computed by solving an initial boundary value problem using a potential flow boundary element or “panel” method. A combined body boundary condition is imposed that incorporates the effects of forward speed, the ship motion (radiation), and the scattering of the incident waves (diffraction). The disturbance velocity potential is computed using a boundary element method with singularity distribution. Once the disturbance velocity potential is computed, Bernoulli’s equation is used to compute the hull pressure distribution.

The disturbance velocity potential can be solved over either the mean wetted surface (the “body linear” solution) or over the instantaneously wetted portion of the hull surface beneath the incident wave (the “body nonlinear” approach). In either case, it is assumed that both the radiation and diffraction waves are small compared to the incident wave and the incident wave slope is small so that the free-surface boundary conditions can be linearized with respect to the incident-wave surface. Similarly, the incident wave forcing (Froude-Krylov) and hydrostatic restoring force can also be computed either on the mean wetted surface or on the wetted hull up to the incident wave.

The combinations of the body linear and body nonlinear solutions of the perturbation potential and the hydrostatic/Froude-Krylov forces provide multiple solution “levels” for the ship-wave interaction problem. These levels are:

- LAMP-1 (body linear solution): both perturbation potential and hydrostatic/Froude-Krylov forces are solved over the mean wetted hull surface
- LAMP-2 (approximate body nonlinear solution): the perturbation potential is solved over the mean wetted hull surface while the hydrostatic/Froude-Krylov forces are solved over the instantaneous wetted hull surface
- LAMP-3 (approximate body nonlinear solution with large lateral displacements): similar to LAMP-2, but the hydrodynamic formulation is revised so that large lateral displacements and yaw angles are accounted for; this allows accurate maneuvering simulations
- LAMP-4 (body nonlinear solution): both the perturbation potential and the hydrostatic/Froude-Krylov forces are solved over the instantaneous wetted hull surface.

Depending on ship geometry and operating conditions,

body-nonlinear hydrodynamics and nonlinear incident wave effects can be important. For most ship motion and wave load problems, the most practical level is the “approximate body-nonlinear solution” (LAMP-2), which combines the body-linear solution of the disturbance velocity potential with body-nonlinear hydrostatic-restoring and Froude-Krylov wave forces. This approach captures a significant portion of nonlinear effects in most ship-wave problems at a fraction of the computational effort for the general body-nonlinear formulation. This is the wave-body hydrodynamic approach used as part of the overall wetdeck slamming analysis.

Several formulations have been implemented to compute the wave-body disturbance velocity potential in LAMP. The basic algorithm involves direct solution of the initial-boundary value problem. The original formulation was a direct transient Green function distribution on the body surface (Lin and Yue, 1990). This formulation is not being used at the current time due to the fact that the transient Green function is highly oscillatory near the free surface when the intersection of the body and the free surface is not near wall-sided.

The transient Green function formulation was later changed in favor of a hybrid singularity distribution method that uses both transient Green functions and Rankine sources (Lin *et al.*, 1999). This approach was implemented in the LAMP System as the “mixed source formulation.” In the mixed source formulation, the fluid domain is split into two regions as shown in Figure 2. The outer domain is solved with transient Green functions distributed over an arbitrarily shaped matching surface, while the inner domain is solved using Rankine sources.

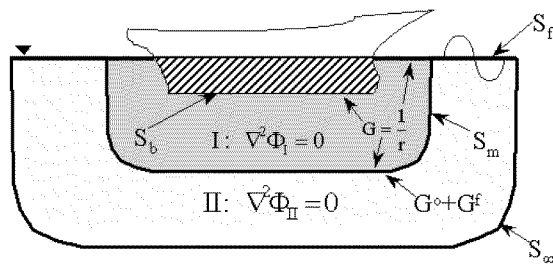


Figure 2: Mixed Source Formulation

The advantage of this formulation is that Rankine sources behave much better than transient Green functions near the body and free surface juncture, and the matching surface can be selected to guarantee good numerical behavior of the transient Green functions. The transient Green functions satisfy both the linearized free surface boundary condition and the radiation condition, allowing the matching surface to be placed fairly close to the body. This numerical

scheme has resulted in robust motion and load predictions for hull forms with non-wall-sided geometries.

Another advantage of the mixed source formulation is that the local free surface elevation is part of the solution, and no additional evaluation is needed as in the case of the transient Green function approach. In addition, a nonlinear free surface boundary condition can be implemented at modest computational cost. In the LAMP System, a 2nd-order free surface boundary condition can be applied on the local portion of the free surface; see more details in Weems *et al.* (2000). However, in the case of a nonlinear free-surface boundary condition in the local portion of the free surface, the matching surface has to be placed further away from the body to minimize errors caused by a mismatch of the free surface.

While the mixed-source formulation works very well for low to modest speeds ($Fr \leq 0.5$), it can be difficult to obtain a stable solution at higher speeds. For this reason, an alternative singularity distribution method was implemented that replaces the external domain and matching surface with a numerical damping region on the outer edge of the free surface (Kim and Weems, 2000). The body and free surface boundary conditions are otherwise identical to those used in the mixed-source formulation. While this singularity distribution method typically requires a considerably larger free surface grid than the mixed-source formulation, it has been successfully applied at speeds up to a Froude number of 0.85. The new method also allows shallow water to be implemented in the hydrodynamic problem by panelizing the bottom or using image sources.

A drawback to time-domain hydrodynamics is the computational cost. To mitigate this, an impulse response function (IRF) based hydrodynamic formulation (Liapis, 1986; King *et al.*, 1988; Bingham *et al.*, 1993) was integrated into the LAMP System to complement the mixed source formulation. In the IRF formulation, velocity potentials are pre-computed for steady forward speed, impulsive motion in up to six modes, and impulsive incident waves for each speed and heading angle. The hydrodynamic problem is thus reduced to a convolution of the IRF potentials with the actual ship motions and incident wave elevation, thereby significantly reducing computational cost without compromising the accuracy of the hydrodynamic calculation.

The IRF potentials are convoluted and summed on a panel-by-panel basis, so that the complete potential distribution of the hull can be computed in the time domain. This allows the panel pressure to be computed directly, including the nonlinear terms in Bernoulli's equation, in the same fashion as in the mixed-source formulation. The only

restriction is that the IRF formulation can only be used with “body-linear” and “approximate body-nonlinear” hydrodynamic solutions. Implementation of the IRF-based approach is described in more detail in Weems *et al.* (2000) and Shin *et al.* (2003).

Seaway Representation

There are several methods in LAMP for modeling a seaway, including a number of standard sea spectra such as Pierson-Moskowitz, Bretschneider, Ochi, and JONSWAP. LAMP also has the capability to use wave height time history data to recreate a phase-resolved representation of actual seaway conditions.

The wetdeck slamming events are highly dependent upon the exact wave conditions and ship motion time history. In the current wetdeck slamming validation study, the wave elevation time history measured by the wave probe in front of the ship was used to reconstruct the phase-resolved wave field. The intent was to recreate, as closely as possible, the actual waves that the ship experienced. In this process, the time series of the wave elevations were decomposed into wave components using a Fourier transform. In the current study, it is assumed that the incident wave has a single heading and travels at a constant speed. A linear wave theory was assumed for the prediction that ignores the higher order effects including wave-wave interaction associated with 2nd order waves. While it is possible to use time histories of multiple wave probes to reconstruct short crested (multi-directional) incident waves or to create higher order wave field reconstructions, these effects are beyond the scope of the current validation effort.

Supplemental Force Modules

While the potential-flow solution of the wave-body hydrodynamic interaction problem typically captures the most important effects for the simulation of a ship in waves, other effects such as viscous and lifting forces and control systems can be significant for particular problems or configurations. To account for these effects, a range of external force and system modules have been incorporated into the LAMP code, including:

- viscous roll damping
- appendage lift and drag
- hull lift maneuvering forces
- course-keeping autopilot
- green water on deck
- internal tanks and flooding
- mooring systems
- fenders and mooring line between ship
- ride control systems

- tank and fin roll control systems
- propulsion systems
- maneuvering forces
- wetdeck slamming pressure and forces.

These modules are implemented in the time domain and compute the forces acting on the ship as a function of the ship motion, incident wave, and other data. They range in complexity from a simple regression-based equation for viscous roll damping to a fully coupled finite-volume flow solution of green water on deck. Many of the modules include multiple options, approaches, and/or levels. Some LAMP System applications that highlight these modules include green water on deck studies (Liut *et al.*, 2002; Zhang *et al.*, 2005), U-tube tank application to parametric roll mitigation (Shin *et al.*, 2004), ship maneuvering in calm water and in waves (Lin *et al.*, 2006), and fenders and cable systems for ship-ship interactions (Weems *et al.*, 2007; Zhang *et al.*, 2007).

In the current study, the most relevant supplemental force modules are the pitch damping modules and the wetdeck slamming module. Details of these two modules are given below.

Supplemental Pitch Damping

In several previous validation studies, LAMP was generally found to predict heave and pitch motions very accurately for several catamaran and trimaran ships (Shin *et al.*, 2003 and Zhang *et al.*, 2003). However, recent applications of LAMP to a candidate high-speed sealift (HSSL) twin-hull ship and the *Sea Fighter* indicate that the LAMP simulation tends to over-predict the pitch motion for these two ships when the peak of the wave encounter spectrum is near the ship’s natural frequency in pitch. A fairly extreme example of this over-prediction is shown in Figure 3.

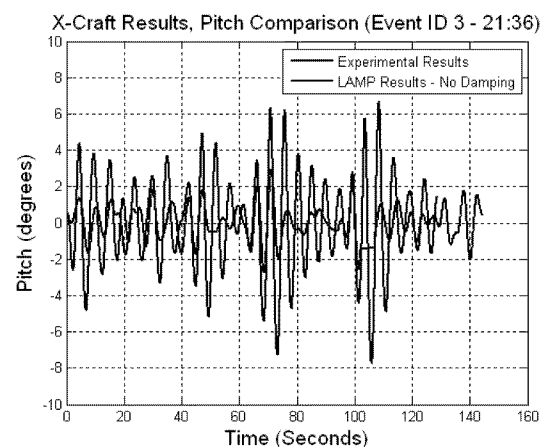


Figure 3: An example of pitch motion comparison without supplemental pitch damping

The specific cause of the over prediction is not clear. It is possible that the fine bows found on these vessels provide relatively little restoring force relative to inertia, allowing other physical phenomena that are in phase with pitch velocity to become significant. These phenomena may include viscous resistance to pitch, flow separation from the fine bow. In general, pitch has also been well-predicted in past LAMP applications to mono-hull ships. Mono-hull ships tend to have far more restoring and hydrodynamic damping in pitch as well as a pitch natural period that is less often near the peak of the encounter frequency for sea conditions of interest. The over-prediction of pitch motion leads to an over-estimation of the occurrence of wetdeck slamming. Therefore, the problem was approached by adding a supplemental pitch damping moment such that the pitch motion of the ship could be correctly captured.

As part of its set of external force modules, LAMP includes an option of adding supplemental forces and moments in any mode of motion in phase with the velocity in that mode. This option includes a linear coefficient, where the force or moment is proportional to the velocity, and a quadratic coefficient where it varies with the square of velocity. Both terms generate a moment or force opposite in sign to the velocity. For pitch damping,

$$ME_5 = -v_5 * KL_5 - v_5^2 * \frac{v_5}{|v_5|} * KQ_5 \quad (1)$$

where

ME_5 = externally applied moment about the ship-fixed y-axis

v_5 = pitch velocity

KL_5 = linear pitch moment coefficient

KQ_5 = quadratic pitch moment coefficient

The non-dimensional form of the linear and quadratic pitch damping coefficients can be expressed as:

$$\begin{aligned} KL_5 &= kl_5 * \left(\frac{\rho}{A} \sqrt{L^3 G} \right) \\ KQ_5 &= kq_5 * \left(\frac{\rho L^5}{A^2} \right) \end{aligned} \quad (2)$$

where

ρ = density of fluid

G = gravitational constant

L = nominal length

A = Angular scale to radians (e.g. 57.296 for degrees)

The pitch damping coefficients can be derived by matching the numerical prediction of pitch motion to either pitch extinction test results and/or a specific pitch motion time history in waves. In the case of the HSSL hull form, a pitch extinction test at zero speed was done and the pitch damping coefficients were obtained by tuning the pitch decay time history to match results of the pitch extinction tests. However, due to the lack of experimental pitch extinction tests for the *Sea Fighter*, the damping coefficients were derived from tuning the damping coefficients so that the numerically predicted pitch motion results match the measured test data. It should be noted that the pitch damping coefficients may be a function of ship forward speed. Figure 4 shows an example of the pitch motion comparison with pitch damping added to the numerical calculation. Although a good comparison can be obtained in this case, further study is required to clearly understand the mechanism of the pitch damping and the process to quantify the magnitude of the pitch damping coefficients.

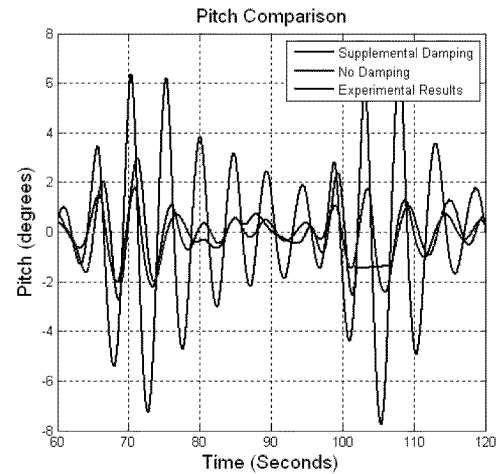


Figure 4: Pitch motion comparison with and without supplemental damping

Overall, implementing supplemental damping terms improves the estimation of pitch relative to the experiment. The goal of the current study is to capture the existence and occurrence of slamming. Tuning the supplemental damping to match the pitch response will promote the particular end goal, while the noted subtleties relative to pitch damping need to be further explored.

Hydrodynamic Formulation of Wetdeck Slamming

Wetdeck slamming involves complex physical processes that are difficult to compute. For instance, as the wetdeck impacts on a body of fluid, it causes sudden changes of the fluid momentum in a localized

region and in a very short period of time; air may be entrapped between the wetdeck, side hulls, and free surface to serve as a cushion; compressibility of the fluid may limit the increase in impact pressure magnitude because of the presence of air bubbles and spray in the impact zone; slamming-related local deformation of the bottom panel and main girder whipping response will occur; and the wetdeck geometry such as curvature, and deadrise angle, also affect slamming characteristics.

Instead of addressing all of the complex issues, this paper adopts an approach that uses a relatively simple approach to capture the most important effects during impact, *i.e.* the time rate of change of the fluid momentum in the local impact zone. In the framework of potential flow, this approach is also called “momentum theory” or “added-mass theory” and had been applied to multihull slamming studies in the past and recent years (Kaplan, 1987; Ge, Faltinsen, and Moan, 2005). It is the approach described in the latter paper (referred to as the GFM approach in this paper) that has been employed and is described in this section.

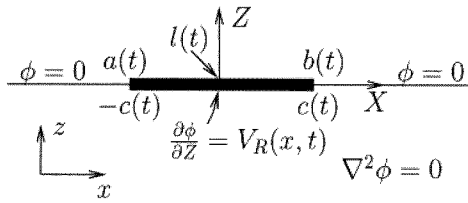


Figure 5: Schematic showing the wetdeck slamming approach in Ge, Faltinsen, and Moan (2005)

As shown in Figure 5, the slamming event in this wetdeck slamming approach is assumed to be taking place in a 2-D longitudinal cross-sectional plane, O-XZ, where the origin “O” is on the free surface, “Z” is vertical up, and “X” is forward to the bow. In this plane, a flat plate moving with the vertical velocity $V_R(X, t)$ is impacting on the undisturbed free surface at $Z=0$. The impact zone is characterized with the instantaneous wetted length $2c(t)$. Denoting the velocity potential associated with this 2-D flat-plate impact as ϕ , the corresponding boundary value problem can be written as:

$$\begin{aligned} \nabla^2 \phi &= 0 && \text{in fluid} \\ \partial \phi / \partial Z &= V_R && Z=0, -c < X < c \\ \phi &= 0 && Z=0, |X| > c \end{aligned} \quad (3)$$

The vertical velocity $V_R(X, t)$ is obtained from the rigid body motion of the ship and can be represented as

$V_R = V_1 + V_2 X$, where V_1 and V_2 are associated with the heave, pitch, and forward speed of the ship and are not a function of X . To be more specific, V_1 represents the difference in the vertical velocity at location X between the flat plate and the incident wave and V_2 represents such difference in rotational (pitch) velocity. The closed-form solution to (3) can be found as

$$\phi(X, t) = (V_1 + \frac{1}{2} V_2 X) \sqrt{c^2 - X^2} \quad (4)$$

This expression is used to derive slamming pressure on the plate using Bernoulli’s equation. Then, the pressure is integrated along the wetted length $2c$ to give the slamming force F_3 per unit width of the wetdeck:

$$F_3 = -\rho \pi c \frac{dc}{dt} V_1 - \rho \frac{\pi}{2} c^2 \frac{\partial V_1}{\partial t} \quad (5)$$

where ρ is the fluid density and F_3 is in the Z direction. It can be shown that the second term in (5) is associated with the 2-D added mass (infinite frequency) of a flat plate of length $2c$ and the first term associated with the time rate of change of the added mass. Using the terminology from GFM, the first and the second terms in (5) are called the slamming term and the added mass term, respectively. During the entry phase, the slamming term is the most significant contributor to the force, while this term is ignored during the exit phase.

In order to use this result for load calculations or to compare to model test pressure panel data, it is necessary to resolve the cut forces into a pressure distribution over the 3-D wetdeck. To do so, it is assumed that the slamming pressure over the wetted length $2c$ has a quadratic distribution, *i.e.*

$$p = \alpha + \beta X + \gamma X^2 \quad (6)$$

where the three coefficients (α, β, γ) are determined by requiring that p goes to zero at the two edges of the wetted length and that the integration of p over the wetted length equals to F_3 . The pressure distributions over each wetted section of each cut are assembled to create a complete wetdeck pressure distribution.

Numerical Implementation of the Wetdeck Slamming Approach

The numerical implementation of the GFM approach into LAMP involves: (1) geometry discretization of the wetdeck, (2) hydrodynamic impact pressure calculation on the wetdeck, and (3) hydrostatic and Froude-Krylov pressures on the wetdeck.

In the geometry discretization, the wetdeck surface between the two demi-hulls is divided into a number of longitudinal strips and each strip is further divided into quadrilateral panels. The center of each panel is the control point where the pressures are to be calculated. Connecting the control points along each strip forms an approximately longitudinal cut along which the hydrodynamic impact calculation is applied.

It can be seen from (5) that the impact force/pressure calculation depends on the calculation of the wetted length $2c$ and its time derivative dc/dt . The wetted length $2c$ on a given longitudinal cut/strip is calculated by computing the intersections between the incident wave surface and the longitudinal cut; the time derivative of the wetted length is calculated by finite differencing across two time steps.

Although the GFM approach is based on a 2-D flat plate and applied to a longitudinal cut, the geometry discretization on the wetdeck allows the approach to be used for more generic circumstances. For instance: (a) along each longitudinal cut, multiple impact zones can be considered simultaneously should they occur; and (b) in the transverse direction on the wetdeck, multiple longitudinal cuts are deployed, which can handle wetdeck slamming in oblique seas, as well as the deadrise angle effect in the transverse direction. However, the 3-D effect of the impact force calculation in the transverse direction is not accounted for with this approach.

One technical issue that needs to be addressed is related to the difference in time step sizes used in the slamming calculation and in LAMP's ship motion calculation. Because of the nature of the slamming event, a smaller time step size as compared to the LAMP time step size is needed to capture the slamming details. This is achieved by employing sub-time steps within a single LAMP time step for slamming calculations. The slamming pressures are averaged over the total number of sub-time steps within each LAMP time step to obtain the "actual" slamming pressure at the LAMP time step.

Another technical issue is related to the limit of the maximum impact pressure in the GFM approach. It is known and can be analytically shown (Faltinsen, 1990) that in this type of potential-flow-based impact pressure calculation, the dc/dt term could be unbounded as $t \rightarrow 0$ under certain circumstances (e.g. a circular cylinder impacts on a flat free surface or a "circular" free surface impacts on a flat plate). Without proper treatment, the maximum impact pressure $p_{max} \rightarrow \infty$ as $t \rightarrow 0$, which is an inherent nature in the GFM approach. However, in reality, p_{max} is always finite and dependent on many factors including impact velocity, air entrainment, and compressibility of water, deadrise angle, elasticity and the scale of the wetdeck. To make the GFM approach more practical, a

procedure of setting the maximum pressure is introduced in LAMP, which is characterized with a non-dimensional coefficient, c_{pmax} . The impact pressure is then limited to a maximum value as follows

$$p_{max} = \frac{1}{2} \rho c_{pmax} V^2 \quad (7)$$

where ρ is the fluid density and V the impact velocity. The advantages of introducing c_{pmax} lie in the fact that it sets an upper limit for the impact pressure; it gives users flexibility to reflect more complex physical process with a relatively simple formula; and it can be determined properly if test/research data are available.

The coefficient c_{pmax} is case-dependent and should be adjusted for different slamming conditions concerning wetdeck geometries, ship speeds, incident waves, etc. Ge, Faltinsen, and Moan (2005) observed that the peak hydrodynamics slamming force is typically about 10 times higher than the combined Froude Krylov and hydrostatic forces. Following this observation, in this study, c_{pmax} was set to 20 such that the maximum slamming force on the wetdeck was about 10 times the peak hydrostatic and Froude-Krylov force.

In addition to the hydrodynamic impact pressure, the buoyancy-induced hydrostatic and incident wave-induced Froude-Krylov pressures are also calculated at the same control points on the wetdeck. All three are added together to obtain the total pressures on the wetdeck panels and then integrated to get the slamming forces. These forces are fed into the equation of motion for ship response calculations.

SEA FIGHTER, FSF-1, WETDECK SLAMMING MODEL TEST AND CODE VALIDATION

Model Setup, Instrumentation, and Test Conditions

Scale model tests of model 5612 (as shown in Figure 6), a 1/15 scale geosym of the U.S. Navy catamaran *Sea Fighter* (FSF-1) were conducted by the Resistance and Powering Division (Code 5200) within the Hydromechanics Department of the Naval Surface Warfare Center, Carderock Division (NSWCCD) at the David Taylor Model Basin (DTMB) to provide wetdeck slamming validation data. The tests were conducted on Carriage II in the deep water basin. The *Sea Fighter* is a 73 meter aluminum catamaran built by the Office of Naval Research (ONR) as an experimental platform to evaluate high speed water jet propelled ships. Model 5612 is a 502.47 cm water jet propelled fiberglass model complete with wetdeck and superstructure. It is appended with geosym appendages on each demi-hull, including a T-foil, a skeg, and the interceptor stiffening plate that resembles a stern flap.

The wetdeck slamming model test is part of a model test task carried out to generate validation data for prediction tools under the SAIC-led ONR HSSL program. The overall model test includes measurement of ship motions, added resistance, wetdeck slamming loads, and side forces and yaw moments for ship maneuvering. Only the part of the model test related to the wetdeck slamming is discussed in this paper.



Figure 6: Model 5612

The model orientation and towing configuration is illustrated in Figure 7, and the layout of the sensors is identified in Figure 8. The model was equipped with deflection-type block gauges to measure drag and side force; three SA-307 Columbia tri-axial accelerometers to measure longitudinal, transverse, and vertical accelerations; and two linear displacement string potentiometers to measure sinkage and trim. Three Senix ultrasonic wave sensors were mounted to the carriage to measure the wave profile: one forward of the model, one aft of the model, and the third off the port side of the model.

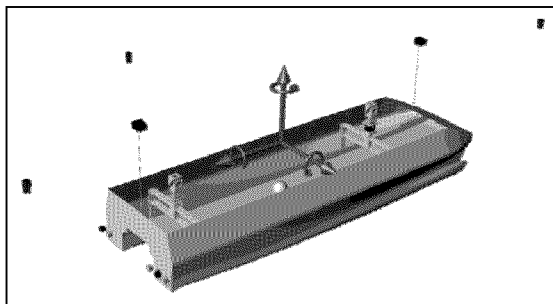


Figure 7: Towing configuration of the model

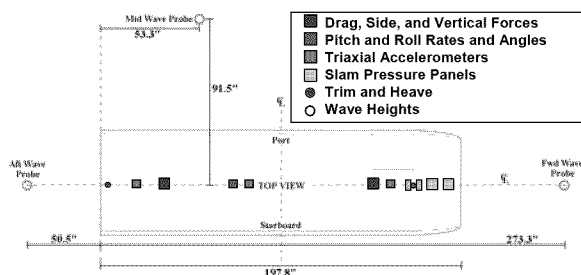


Figure 8: Instrumentation layout

In addition, four strain gauged PVC panels measured slam pressures. As shown in Figure 9, two separate sized PVC slam panels, 3.81 x 7.62 and 7.62 x 7.62 cm, were installed in the forward wetdeck. The

locations selected for the PVC panels were guided by the slamming experiences during the *Sea Fighter* trials. The panels are calibrated to provide the average pressure over the panel area and are hence incapable of returning the maximum peak pressures. Additional pressure sensors, which require further analysis, were installed surrounding the slam panels to reveal the maximum peak pressures. These sensors are identified in Figure 9 by the black dots surrounding the forward slam panel. The pressure sensors were installed in the 27.94 cm wide, 64 mm thick fiberglass wetdeck stretching the full length of the model.

Two separate data acquisition systems were utilized during the test. A system operating at a sampling rate of 100 Hz was utilized to capture the motion responses and the incident wave profile. The slam pressures were sampled on a separate system operating at a sampling rate of 65 KHz. Time synchronization was ensured by triggering the high rate system using the low rate system. For reassurance, multiple channels were sampled on both systems thereby allowing comparison of time histories.

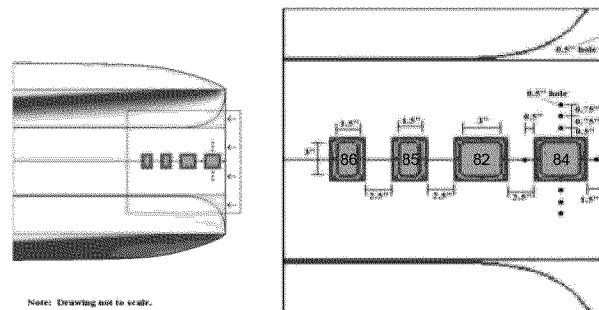


Figure 9: Slam panel placement

The model test included two ballast conditions. In the first condition, the model was ballasted to 1413 tonnes (486 Kg) and was free to heave, pitch, and roll. The detailed model configuration at this ballast condition is listed in Table 1. In the second condition, the model was ballasted to 2113 tonnes (727 lbs) and was fully restrained; Table 2 gives the model configuration at this ballasted condition. In both ballasted conditions, all the model appendages were attached (T-foils, skegs, and interceptors).

In both ballast conditions, the model was tested in head sea regular wave conditions only. For the 1413 tonnes ballasted condition, three wave periods (1.80, 2.20, and 3.15 seconds) were chosen to span the modal periods experienced in sea state 4. The three wave periods corresponded to λ/L (wave length / ship length) = 1.0, 1.6, and 3.2. Three wave heights of 12.7cm, 15.24cm, and 17.78cm were selected for the model test. The wave heights resulted in steepness ranging from 1/122 through 1/25. The model was towed at $F_n = 0.17, 0.3, 0.5$, and 0.9 corresponding to

speeds of 8.9, 15.6, 26, and 46.9 knots. Reynolds numbers range from 2.81×10^8 to 1.48×10^9 .

Table 1: Model configuration for the 1413 tonnes (486 Kg) ballast condition

Free To Pitch And Heave	Full-Scale	Model	
Parameters	(m)	(cm)	
Length (LOA)	75.37	502.47	
Length (LBP)	73.00	486.66	
Beam (BPX)	21.05	140.33	
Beam (BWL)	20.31	135.43	
Draft (avg)	3.64	24.29	
Displacement (tonnes, Kg)	1413	485.9	
LCG, + fwd of Midships	-6.75	-45.03	
TCG, port of CL	-0.18	-1.20	
VCG, above keel	6.54	43.61	%LOA or %BPX
VCG, above waterline	2.90	19.30	
Pitch gyradius (about cg)	22.79	151.95	
Roll gyradius (about cg)	6.31	42.08	
Yaw gyradius (about cg)	22.64	150.96	30.04%

Midships = 251.31cm fwd of transom = midpoint of LOA

Table 2: Model configuration for the 2113 tonnes (727 Kg) ballast condition

Free To Pitch And Heave	Full-Scale	Model	
Parameters	(m)	(cm)	
Length (LOA)	75.37	502.47	
Length (LBP)	73.00	486.66	
Beam (BPX)	21.05	140.33	
Beam (BWL)	20.40	135.98	
Draft (avg)	4.97	33.15	
Displacement (tonnes, Kg)	2113	726.6	
LCG, + fwd of Midships	-7.68	-51.23	
TCG, port of CL	-0.12	-0.79	
VCG, above keel	6.83	45.56	%LOA or %BPX
VCG, above waterline	1.86	12.42	
Pitch gyradius (about cg)	22.71	151.42	
Roll gyradius (about cg)	5.29	35.23	
Yaw gyradius (about cg)	22.63	150.88	30.03%

Midships = 251.31cm fwd of transom = midpoint of LOA

For the 2113 tonnes ballasted condition, the model was tested in 0.56 HZ regular waves (wave period = 1.8 sec or $\lambda/L = 1.0$). Four wave heights were used: 14.99cm, 15.24cm, 15.75cm, and 16.00cm. The model was towed at the same four speeds as specified for the 1413 tonnes ballasted condition.

Selected Model Test Results

Several cases were selected for the current LAMP validation study. In this paper, validation results from one case are discussed in detail. This case is referred to as Spot 149. The associated test condition for Spot 149 is given below.

Table 3: Spot 149 test condition

Constraint	2-DOF
Full scale speed	15.6 Knots
Full scale displacement	1413 tonnes
Wave length / ship length	1.6
Model scale wave height	17.78 cm

The model test measured the wave probe elevations, drag force, heave and pitch motions and rates, CG accelerations, and the time history of the wetdeck pressure at the pressure panels. Figure 10 shows the pressure time history at the four pressure panels. A series of frames taken from video of a single wave encounter cycle during Spot 149 is shown in Figure 11. It can be seen clearly that the slamming event was severe, and it is expected that the wetdeck would have experienced a high pressure during this event. The magnitude of the slamming pressure depends on the geometry of the wetdeck and the relative motion between the wetdeck and the water surface.

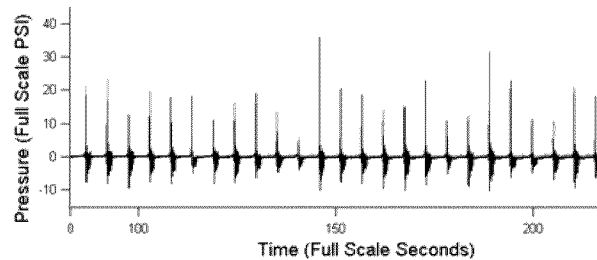


Figure 10: Time history of the wetdeck pressure at pressure panels

A close-up view of the pressure time history is given in Figure 12. It can be seen in the figure that the slamming pressure at panel 86 is the largest among the pressures measured from the four slam panels. This shows that the maximum slamming pressure could occur at a location other than the bow, depending on the relative motion and phasing between the ship and the wave motions. More model test results will be shown in the next section, where the numerical predictions are compared with the model test results.

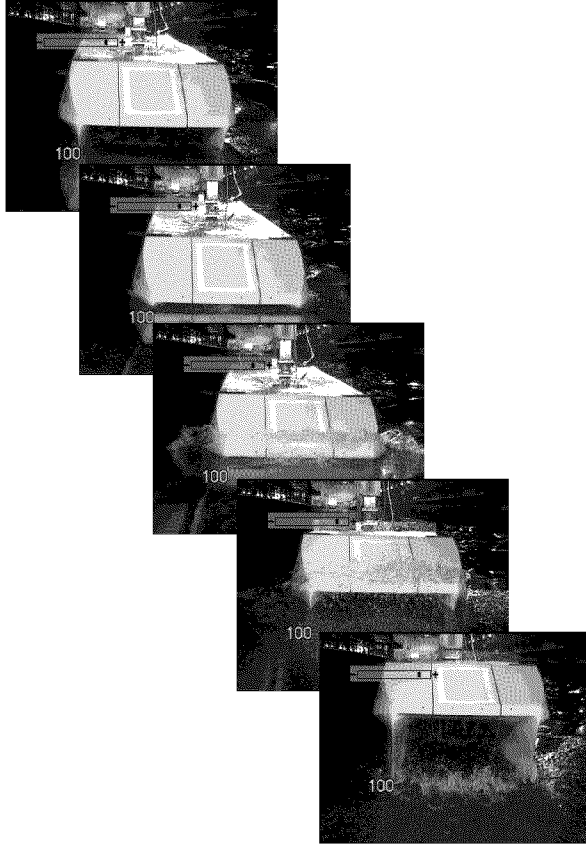


Figure 11: Ship motion and wetdeck slamming from a single wave encounter in the model test

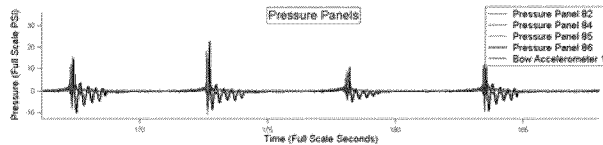


Figure 12: Close-up view of the wetdeck slamming pressure time history

LAMP Setup Numerical Computation

In order to validate the numerical method against this test data, LAMP simulations were made of *Sea Fighter* in the model test loading and wave conditions. Figure 13 shows the LAMP hull geometry developed for the *Sea Fighter* while Figure 14 shows a typical computational geometry panelization consisting of the underwater portion of the hull and a local portion of the free surface. For the LAMP potential flow panelization, 606 panels are distributed over the wetted hull surface and a rectangular free surface domain of 19m x 12m (model scale) is modeled with 4800 panels. For long-crested head sea calculation, the symmetry of the

hydrodynamic problem requires only half of this geometry to be used.

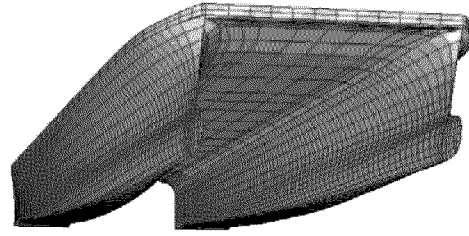


Figure 13: LAMP hull panelization for *Sea Fighter*

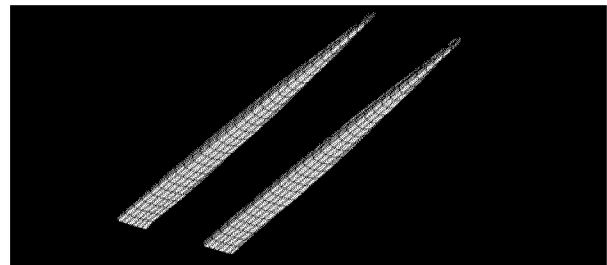


Figure 14: Panelization on the body and near field free surface

For the wetdeck slamming calculations, the wetdeck was independently discretized as shown in Figure 15. The panels on the wetdeck were created such that the control points on each longitudinal strip are aligned along the corresponding longitudinal cut. On the panelized half of the wetdeck ($y > 0$), 8 longitudinal strips and 232 quadrilateral panels were used.

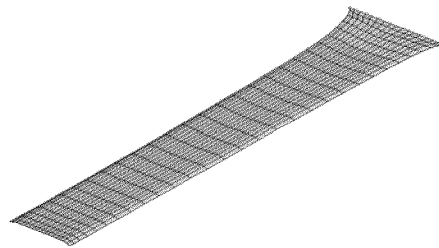


Figure 15: Panelization of the wetdeck

For *Sea Fighter* motion and load calculations *without* the wetdeck slamming calculations, the time step in the LAMP simulation can typically be set to 0.01 seconds or larger. For the calculations including wetdeck slamming that are presented in this paper, the LAMP time step size was reduced to 0.002 seconds to obtain better resolution of the slamming event. Within the slamming module, three sub-time steps were used to capture more details of the slamming process.

LAMP Validation Results

The results of the LAMP validation study using the model test data at Spot 149 are presented in this section. All results are shown in the time domain and match the time values provided in the model test results. All results are in model scale metric units. The first step of the validation was to use a wave reconstruction technique to reproduce the model test incident wave for the LAMP calculation. Figure 16 shows the wave elevation time history at the front wave probe and the LAMP wave field evaluated at the probe location. The error is well within 1%.

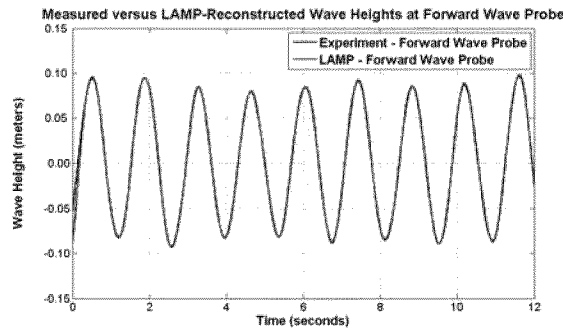


Figure 16: Incident wave elevation comparison

In Spot 149, the wavelength was 1.6 times the ship length and the encounter frequency was near a resonance point for pitch. The heave comparison is given in Figure 17 and the pitch comparison is given in Figure 18. The model test result shows a mean pitch of about 0.06 degrees bow down (+ pitch angle in Figure 18 is bow down), with a maximum bow down close to 3.5 degrees and bow up about 3.1 degrees. LAMP indicates a mean pitch close to zero with pitch amplitude of about 3 degrees. In general, the LAMP predictions and the model test results compare very well in both heave and pitch. It should be noted that supplemental pitch damping was included in the LAMP calculation, as discussed earlier in the mathematical formulation section.

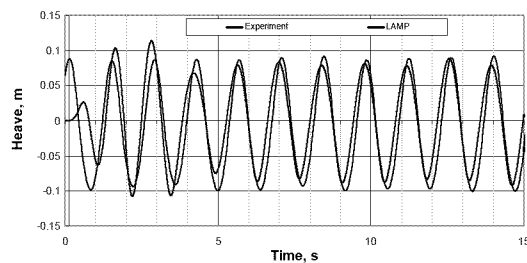


Figure 17: Spot 149, heave motion comparison

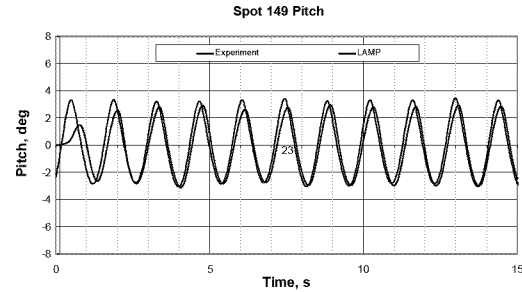


Figure 18: Spot 149, pitch motion comparison

Figure 19 compares the vertical acceleration at the bow. The model test result seems to be largely influenced by structural vibration. LAMP closely predicts the incidence of maximum acceleration due to the slam, but the experiment has a much higher peak plus a significant high frequency component.

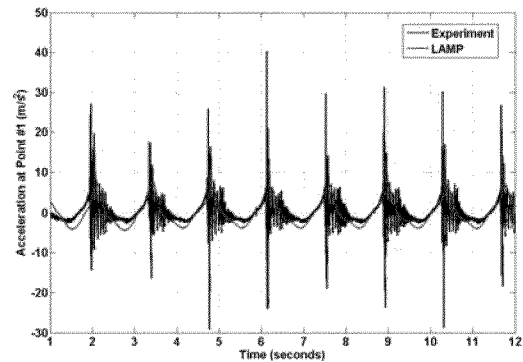


Figure 19: Spot 149, bow acceleration comparison

Figure 20 compares the pressure at Panel 82. Both the time of occurrence and the peak pressure match well. The model vibration can be seen in the pressure after the peak. The LAMP calculation does not consider negative pressures or structural response.

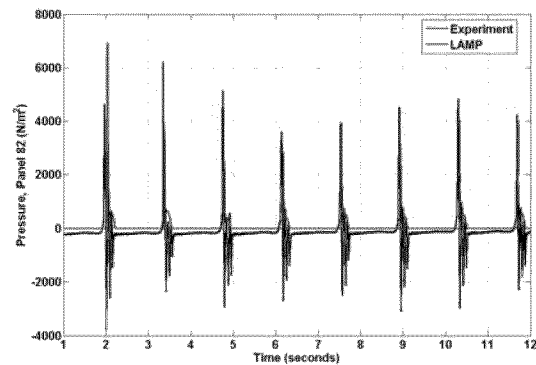


Figure 20: Spot 149, pressure at panel 82

Overall, the validation study showed that the current numerical simulation method is generally suitable for

wetdeck slamming calculation. However, two major remaining research and development issues are quantification of pitch damping for multihull and the value of c_{pmax} .

SEA FIGHTER, FSF-1, FULL-SCALE SEA TRIALS AND CODE VALIDATION

Sea Fighter Sea Trial Setup and Test Conditions

To obtain full-scale qualitative and quantitative multihull ship motion and wetdeck slamming data, a sea trial of the *Sea Fighter* was carried out from April 18-21, 2006 (Fu *et al.*, 2007). In the sea trial, the *Sea Fighter* was fully instrumented with a wide assortment of sensors, including fixed and scanning LIDAR, X-Band radar, IMUs, ultra-sonic wave height sensors, strain gauges, stereo camera systems, directional wave buoys, GPS, and 6-DOF motion packages. The acquired data was to be used to validate various computational tools and processes. In addition to the analysis of the ship motions, particular attention has been paid to the slamming events, the incident wave profile, and the observed wave field near and at a distance from the vessel with the goal to develop an understanding of the conditions leading to slamming events.

The placement and overlap of the wave field sensors was critical to the validation of the phase-resolved wave field reconstruction and prediction tools. During the experiment, the ultra-sonic sensors recorded the incident wave profile just near the bow, LIDAR, and stereo photogrammetry were used to measure the wave field from the bow out to 350 feet, while the X-Band radar was used to measure 350 feet out to a mile. The time history of the incident wave was provided for validation efforts of the phase-resolved wave field reconstruction and prediction tools.

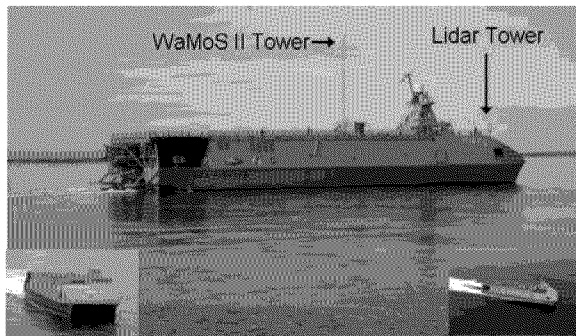


Figure 21: *Sea Fighter*

Figure 21 shows the *Sea Fighter* including the placement of LIDAR and X-Band radar. While not shown in the image, the ultra-sonic sensors were located in the bow and the stereo camera systems were placed on the foremost point of the upper deck.

The trial took place over four days, departing Esquimalt, British Columbia, Canada, on 18 April and arriving in San Diego on 21 April. Table 4 below shows the range of the significant wave height and period as well as wave heading for the test period. This data was obtained from the onboard TSK sensor, a deployed Neptune wave buoy, and NOAA buoys. Ship speed was 40 knots for the first day and dropped to 20 knots for the rest of the cruise.

Table 4: Wave data from *Sea Fighter* rough water trial (from Fu *et al.*, 2007)

Date	Time GMT	Hs m	To sec	Ts sec	Dir deg - M	Sensor
4/19/06	300	2.6	10	-	WSW	46087*
4/19/06	427	2.5	9.1	7.7	WSW	46087
4/19/06	455	2.4	8.3	-	WSW	46087
4/19/06	1500	1.5	11	6	NNW	Neptune Buoy
4/19/06	1915	2	6.8	-	-	Onboard TSK
4/19/06	2155	1.9	9.1	-	-	Onboard TSK
4/20/06	130	1.9	9.1	7.4	-	Onboard TSK
4/20/06	1500	2.3	7.1	-	332	46028**
4/20/06	1600	2.3	6.7	-	324	46028
4/20/06	1627	2	7.4	-	321	Neptune Buoy
4/20/06	1655	2.1	6.9	-	6	Neptune Buoy
4/20/06	1825	2.6	5.9	16.4	-	Onboard TSK
4/20/06	2300	2.3	16.1	7.1	308	46028
4/20/06	2320	2.7	6.3	16.4	-	Onboard TSK

Table 5 represents the *Sea Fighter* characteristics pre- and post-departure. The listed values were used as the starting point for the initial geometric setup of the computational codes.

Table 5: *Sea Fighter* characteristics

Experiment Setup		
Ship Displacement	Departure:	1,417,000 kg.
	Arrival:	1,243,000 kg.
LOA	262 ft	79.86 m
Beam	72.16 ft	21.99 m
LWL	239.44 ft	72.98 m
LCG	Departure:	98.1 ft
	Arrival:	99.8 ft
		30.42 m

Selected Sea Trial Results

As discussed earlier, the objective of this sea trial was to obtain full-scale qualitative and quantitative multihull ship motion and wetdeck slamming data. The most notable slamming events are identified in Table 6 below. During these four slamming events, the significant wave height roughly ranges from 2.3m to 2.7m.

Table 6: Summary of slam events
(from Fu *et al.*, 2007)

Slam Event	Date	Time (GMT)	Speed (Knt)
1	19-Apr-06	2:33	30
2	20-Apr-06	19:30	19.8
3	20-Apr-06	21:36	16.4
4	20-Apr-06	22:08	15.8

For each of the slam events, four accelerometers have been integrated in time to derive ship motion histories. The resulting time series of heave and pitch encompassing slam event 3 (beginning at 21:36 GMT) is shown in Figure 22.

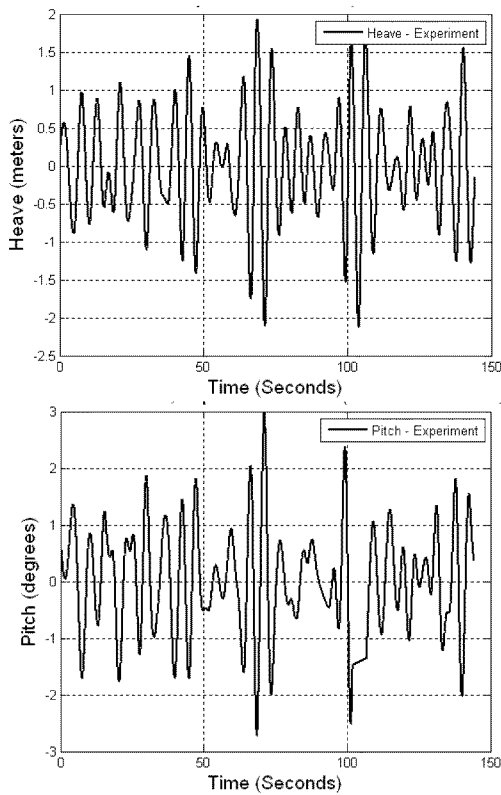


Figure 22: Heave and pitch motion, slam event 3

As mentioned before, the time history of the incident wave was required for the validation of the time-domain numerical simulation method. To compute the incident waves for each of the slamming events, the wave record measured by the ultra-sonic sensors near the bow was used. This data was correlated with the integrated accelerometer data and was corrected for pitch, roll, and heave motion. The recorded time history of the incident wave elevations was decomposed into wave components using the Fourier transform. These wave components were used to represent the actual phase-resolved wave field in the time domain computation. Since only the data from

one ultra-sonic wave probe was used and the ship was operating very close to a head sea condition, it is assumed in the numerical simulation that the ship is operating in pure long-crested head seas. This assumption can be relaxed in the future once the X-Band radar data becomes available.

Comparison of the Numerical Simulation Results and the Measured Full-Scale Sea Trial Data

Figure 23 compares the computed and measured heave and pitch motions for slam event 3. The overall comparison is very encouraging, considering the assumptions made in the wave reconstruction. This result is significant since it shows that the wave field reconstruction technique can be used to obtain a phase-resolved wave field for a full scale sea trial to understand the ocean environment during the sea trial and to quantify wave input to the code validation.

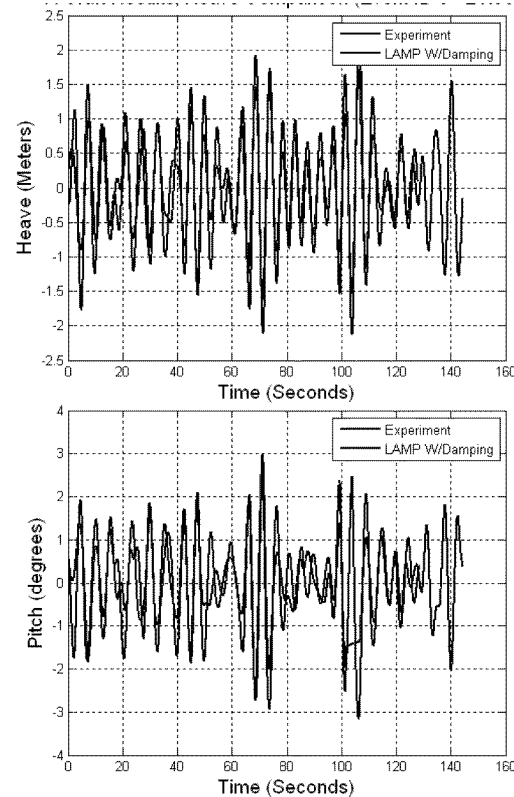


Figure 23: Comparison of experimental and computational motions, slam event 3

In the motion comparison for this case, there is a substantial difference in the pitch motion near the 105 second mark but this appears to be the result of an anomaly in the experimental data. The anomaly is likely a result of a slamming event that saturated the sensors or disrupted the data recording process.

To check the numerical prediction of wetdeck slamming, four locations were chosen along the centerline wetdeck and the relative motion and pressure history at each location were computed. A wetdeck slam was identified when one or more of these locations become submerged with sufficient relative velocity. These positions are shown in Figure 24.

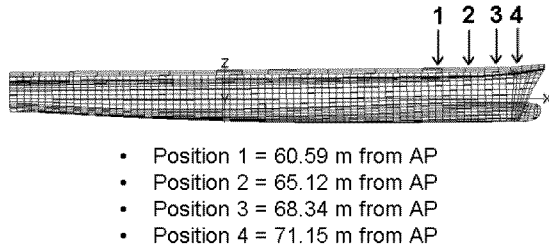


Figure 24: Locations of computed pressure in calculations recreating sea trial slamming events

Figure 25 shows the time history of the computed slamming pressure around the time of the sea trial's slam event 3. It clearly indicates that the wetdeck slamming occurs at around 70 ~ 75 sec, and near 105 sec. The ship motion and wetdeck slamming phenomenon observed in the numerical simulation are very similar to those observed in the sea trial (Fu *et al.*, 2007).

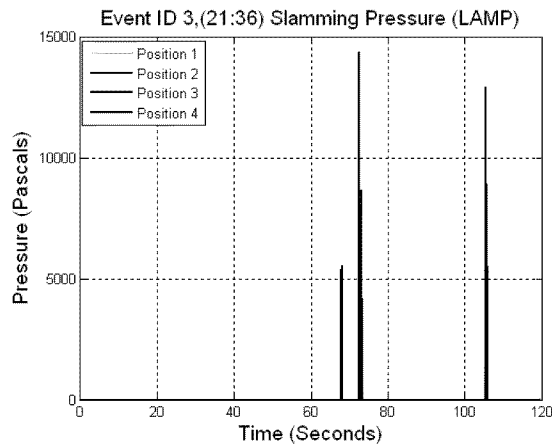


Figure 25: Numerical time history of computed pressure during slam event 3

From the computation results, it is observed that during a typical impact event, there is a very sharp peak pressure initially followed by a more rounded hump primarily caused by hydrostatic and Froude Krylov pressure. To illustration this phenomenon, Figure 26 shows a close-up view of the slamming pressure near $t = 105$ sec at the four positions indicated above. The figures shows that position 2 did not experience a sharp

peak pressure, indicating a relatively small impact velocity, and position 1 was not even wetted.

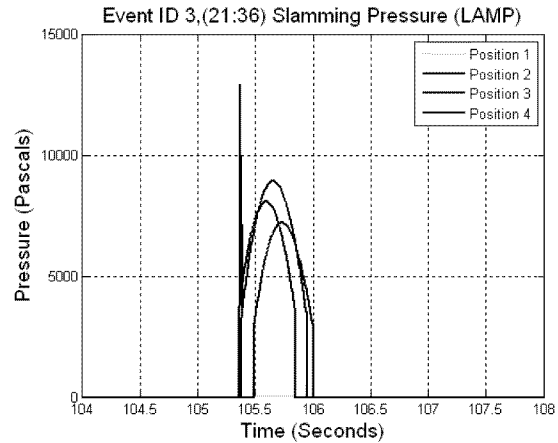


Figure 26: Detail computed pressure distribution near time = 105 sec.

Figure 27 shows a time history of the total force on the wetdeck time around this event. The initial spike corresponds mostly to impact effects while the following hump is mostly from the hydrostatic and Froude Krylov contribution. The peak impact force is about 10 times higher then the following hump.

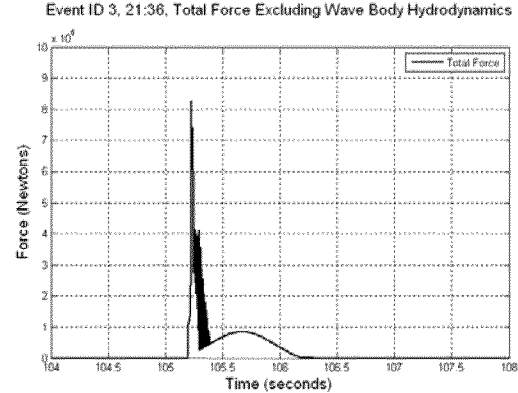


Figure 27: Computed force distribution near time = 105 sec.

Overall, the comparisons of the numerical simulation results and the full scale sea trial data are reasonably good. This validation study is very encouraging since it clearly shows that the wave field reconstruction technique could be used to obtain the phase-resolved wave field in full scale sea trial to quantify the wave input to the code validation process.

CONCLUSIONS

In this paper, a time-domain numerical simulation method was presented for the prediction of motions and wetdeck slamming loads on high-speed catamarans. The mathematical formulation and the validation study using both model test data and full-scale sea trial results are discussed. Several conclusions can be drawn from the current study:

- The validation study shows that the current numerical simulation method can capture the overall ship motion, occurrence of wetdeck slamming events, and wetdeck slamming force/pressure reasonably well.
- Although it was shown in prior validation study that LAMP predicts heave and pitch motion pretty accurately for multi-hull, supplemental pitch damping terms are needed for the HSSL hull form and for the *Sea Fighter* to predict the pitch motion accurately. The pitch damping coefficients are likely to be speed- and geometry-dependent.
- The wetdeck slamming pressure is calculated using the GFM approach. The maximum pressure is controlled by the maximum impact pressure coefficient c_{pmax} . In the current study, c_{pmax} is set to be 20 based on an observation in Ge, Faltinsen, and Moan (2005).
- The GFM approach is a 2-D method. The applicability of this approach to 3-D slamming and complicated wetdeck configuration is limited. More advanced 3-D approaches are desired.
- A rigid body assumption is used in the current numerical simulation approach. Local structural deformation and structure vibration will affect the local pressure peak of the slamming event.
- The model test results show that the maximum impact loads do not necessarily occur at the forward most portion of the wetdeck. This result needs to be taken into consideration during structural design of the wetdeck region.
- In the validation study using the full-scale sea trial data, it is important to properly characterize the incident wave field. Using the ultra-sonic sensor as a profiler of the incident wave has been successful. The phase-resolved wave field reconstruction and prediction codes that have been implemented have been initially validated by the direct comparison to the experimental observations as well as the success of the motion comparisons. Additional work is needed to characterize the short-crested incident wave field.

ACKNOWLEDGEMENTS

LAMP System development began with a 1988 DARPA project for advanced nonlinear ship motion simulation, and has continued under the sponsorship of the U.S. Navy, the U.S. Coast Guard, the American Bureau of Shipping (ABS), and SAIC's IR&D program. The authors would like to thank Dr. L. Patrick Purtell of ONR for his support of the HSSL program and the general LAMP development efforts throughout the years.

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